Numerical Modeling & Analysis of Plume Migration Effects on Public Drinking Water Wells at Lake Mirimichi

By

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ABSTRACT

This thesis involves the use of MODFLOW and MODPATH in the development of a numerical groundwater model of the Lake Mirimichi area in Plainville Massachusetts. The potential effects of a plume migrating from a landfill on the proposed drinking water wells is investigated with the help of plume tracking. The Plainville Landfill is a municipal landfill and has been in operation for almost 25 years. A leak in the liner has caused a plume to emanate from the southwest corner toward Lake Mirimichi, which is downgradient of the landfill. Volatile organic carbon concentrations such as vinyl chloride and 1,4 Dichlorobenzene have been detected above the Massachusetts Maximum Contaminant Level and concerns have arisen as to whether the plume will be hazardous to the community around it. Moreover the town of Plainville has proposed public drinking water wells to be located at the southern shore of Lake Mirimichi. Various scenarios were simulated to investigate conditions that may enable the plume to reach the wells. Low recharge rates, lower lake levels and both high and low sediment conductivities were applied to the model to simulate drought conditions and worst case conditions. The proposed pumping rates imply minimal effect on well contamination under drought conditions. When the lake levels are increased by a feet and sediment conductivities reduced to 20 % of normal conditions, particle tracking reveals few particles reach the southern portion of the lake from which the wells draw water. Backward particle tracking was also performed around the Lake Mirimichi wellfield to determine its source under the different scenarios. The results show minimal withdrawal from Lake Mirimichi, about 30 %, but the majority is predicted to be from a surface water source.

Thesis Supervisor: Charles F. Harvey
Title: Associate Professor of Civil and Environmental Engineering

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Dedicated to:
Engr. M. A. Rahman
My dad who introduced me
to this wonderful profession.

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1. INTRODUCTION

The Plainville Landfill is located in the town of Plainville, Massachusetts, and is one of the largest landfill complexes in the state. The landfill was in operation for twenty-three years from 1975 until its capping (1998). In the early 1980's a groundwater contaminant plume was detected leaking out of the southwest corner and has since been the subject of many investigations.

Aquifers in New England are productive in supplying drinking water because the underlying glacial outwash serves as an efficient storage system for freshwater. The Plainville area, being part of the Taunton River Basin, acts as one such aquifer. But presently, the increasing population in the area is stressing municipal water supply, and the number of potential sites for wells has diminished due to development. The towns of Wrentham, Plainville and Foxborough have plans to install municipal drinking water wells in the area. The Plainville landfill is in close vicinity to these proposed wells, and the existing contaminant plume poses a threat to the groundwater quality. Unmonitored private wells are scattered around Lake Mirimichi and are also threatened. These may cause health hazards to their owners as a result of this plume. The supply wells and its influence on the groundwater plume will be investigated in this study.

1.1 BACKGROUND

The Plainville Landfill is located approximately 70 miles southwest of Boston Massachusetts in the town of Plainville as shown in Figure 1.1 and Figure 1.2. The Plainville Landfill covers approximately 139 acres in Plainville, 47 acres in Wrentham and 1 acre in Foxborough. The actual landfill footprint, however, occupies approximately 92 acres in Plainville. The remaining acreage consists of support buildings, sedimentation ponds and an old quarry. The landfill is bordered to the south, by Interstate 495, and Rabbit Hill Pond and Stream, to the west. To the North lies the cranberry bogs; on the east is a private campground and woodlands of Foxborough. Lake Mirimichi lies south west of the landfill.

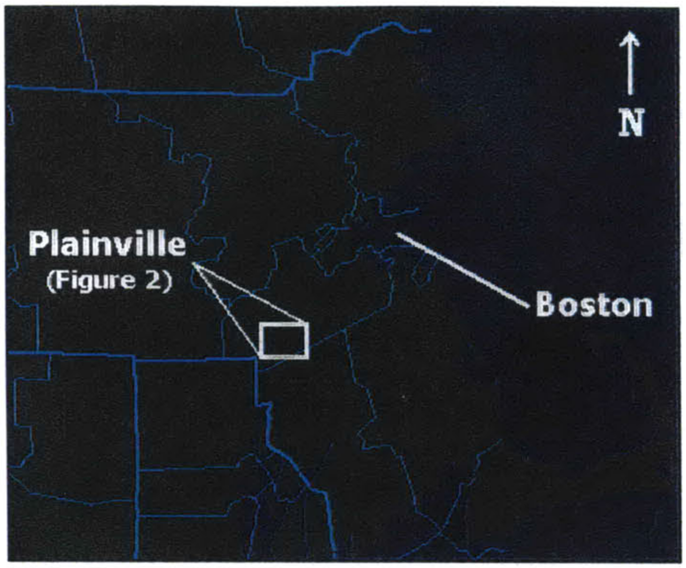

FIGURE 1.1: PLAINVILLE, MASSACHUSETTS

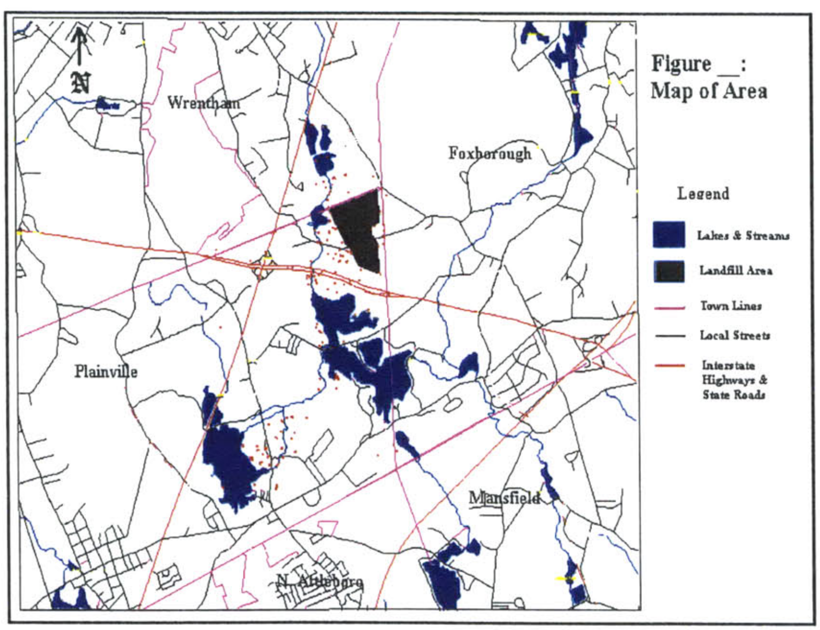

FIGURE 1.2: MAP OF AREA

1.2 Physical Characteristics

The regional topography comprises of buried glacial outwash valleys underlain by bedrock. The outwash valley acts as a highly productive aquifer that provides groundwater resources. The valley consists of glacial outwash that overlies fractured bedrock beginning north of the cranberry bogs and trending southward from Rabbit Hill Pond towards Lake Mirimichi. The glacial outwash consists of fine to coarse sand, some gravel, and little to trace amounts of silt and clay and exhibits hydraulic conductivities ranging from 0.00003 ft/day to 148 ft/day (Eckenfelder, 1998). Approximately the top ten feet of the bedrock is fractured and provides groundwater resources to the Plainville area. Glacial till borders the outwash valley on both the east and west as outlined by the red line in Figure 1.3. The glacial till is nonconductive, (hydraulic conductivity ranges from 3.1 ft/d to 45 ft/d), and creates a channel for groundwater flow through the outwash layer (Eckenfelder, 1998). Details of the site characterization are outlined in the project report, Plainville Landfill Investigation (Chen, Rahman & Woodworth, 1999)

The aquifer system underlays the Plainville outwash valley which is unconfined and is recharged from precipitation, at a rate of approximately 21 inches annually. Groundwater flow, within both the outwash and fractured bedrock layers, is generally northeast to southwest. These two layers are hydraulically connected.

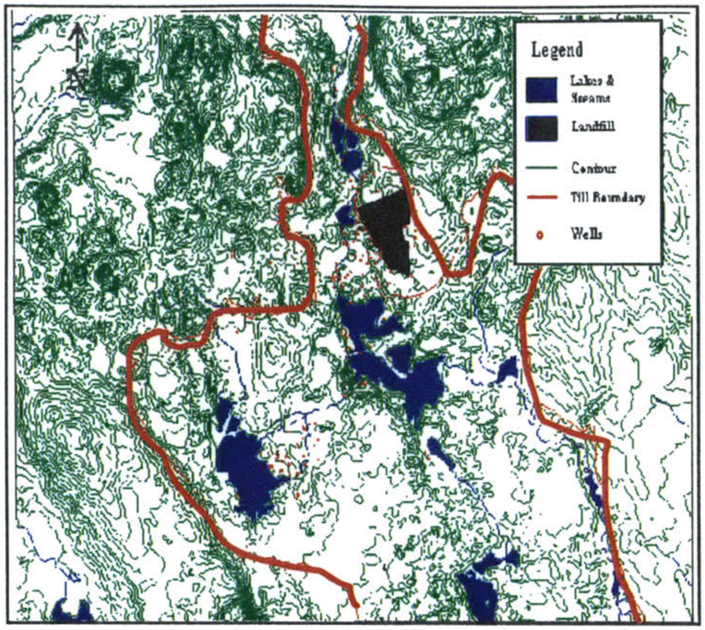

FIGURE 1.3: GLACIAL OUTWASH VALLEY

1.3 ANALYSIS DESCRIPTION

The purpose of this report was to investigate the potential pathways for the contaminant plume and its effects on the surrounding drinking water supply wells. Lake Mirimichi is hydrologically down-gradient of the landfill and acts as a source for the proposed supply wells. The underground landfill leachate plume is presently located at the northern edge of the lake and is infiltrating into the surface water through the lake sediments. Turning the pumps on could allow contaminant migration towards the wells by flowing under the lake as shown in Figure 1.4. A numerical groundwater model representative of the current groundwater hydrology was developed using MODFLOW. This model was then coupled with particle tracking to identify the potential pathways of the plume. The model-input parameters were later altered to simulate seasonal variations, and the results explained in the conclusions.

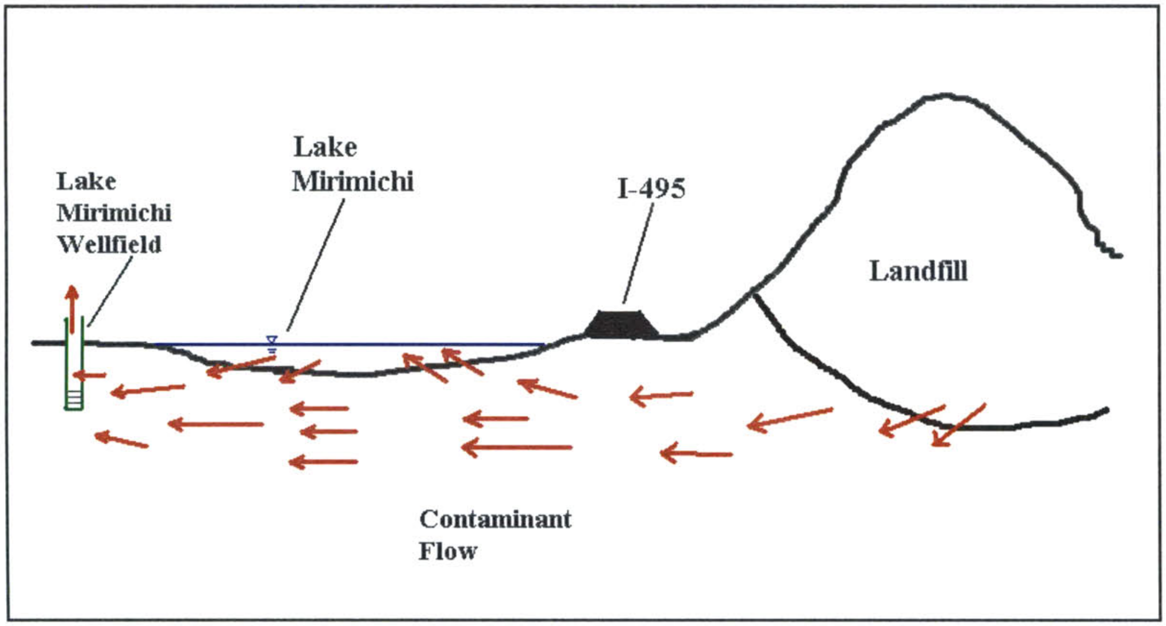

FIGURE 1.4: HYPOTHESIZED FLOW PATHWAY

1.4 METHODOLOGY

The numerical groundwater flow model described in Chapter 3 of the project report (Chen, Rahman & Woodoworth, 1999) coupled with particle tracking can be used for delineating contributing areas of proposed supply wells. The numerical groundwater model was a basis to determine the potential pathways of the migrating plume. This model was further modified to include pumping wells, to ascertain their zone of influence and to evaluate the extent of the plume as a result of pumping.

The computer program MODPATH, developed by USGS (Pollock, 1989), is a particle tracking routine that takes output from steady-state MODFLOW simulations and computes the three dimensional pathline of a water particle from the source to its fate. Particle tracking can help identify the aquifer source area from which a well is pumping water.

This study followed the procedure outlined below to determine the zone of influence or the contributing area of a well:

1) Construct a pre-pumping water table contour map.
2) Perform particle tracking at non-pumping conditions to assess the extent of the plume.
3) Install the wells and determining their zone of influence.
4) Predict drawdown of the pumping wells.
5) Perform particle tracking while the pumps are on-line.
6) Assess whether the plume will reach the wells at the proposed pumping rate.

2. GROUNDWATER NUMERICAL MODEL

The model area embodies typical New England geology. The stratified-drift aquifer consists of outwash that has been deposited by glacial meltwaters when glaciers retreated from New England (USGS Water-Supply Paper 2275, p. 250). These depositions created small, permeable valley-filled aquifers in most of Massachusetts. Specific geologic details of this study's area of concern are provided in the project report, Plainville Landfill Investigation (Chen, Rahman & Woodworth, 1999).

2.1 MODFLOW CAPABILITIES

The USGS MODFLOW, an industry standard for groundwater flow and contaminant transport modeling, was used in conjunction with the user-friendly interface developed by Waterloo Hydrogeologic, Inc. The model determines the distribution of hydraulic head and groundwater flow field over time and space. MODFLOW is described by its authors as a modular computer program for three-dimensional groundwater flow modeling (McDonald and Harbaugh, 1988). MODFLOW can be used for steady state or transient simulations; for this study, the model was run in steady-state mode to evaluate long-term average behavior of the groundwater system. In vertical geometry, MODFLOW allows representations as three-dimensional, quasi-three-dimensional, or two-dimensional. This study utilized the three-dimensional capability.

2.2 Model Development

2.2.1 Discretization

The model area and finite-difference grid is shown in Figure 2.1. Natural boundaries were chosen to define the model. To the east and west, no-flow boundaries were delineated by the low conductivity till deposits. The outline of this was determined from a USGS map (USGS 1973) and a USGS topographic map of the area (USGS 1987).

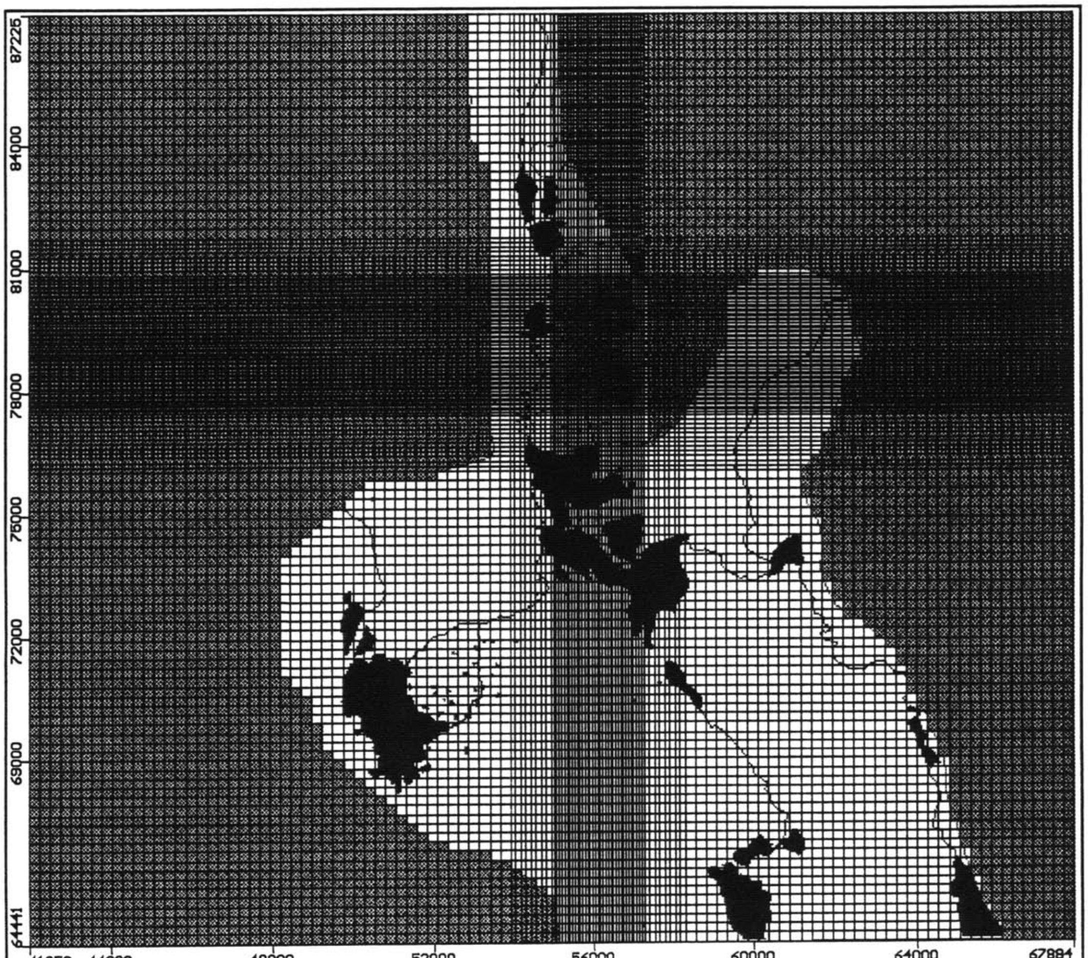

FIGURE 2.1: MODEL AREA AND FINITE DIFFERENCE GRID

The northern boundary and southern boundaries were set at a sufficient distance so that the heads specified at these edges would not affect any evaluation in this study.

The numerical grid consisted of 155 rows and 135 columns. The grid was further refined over the areas of interest – namely, the landfill, remediation site, and drinking water wells by Lake Mirimichi. The resolution of these cells ranged from about 3,700 square feet to 60,000 square feet. For proper solution convergence, the requirement that the difference in area between adjacent cells must not exceed 50% was followed.

2.2.2 Soil Layers

Figure 2.2 is a typical cross-section of the Plainville area. It illustrates the soil layers devised into the numerical model. The site was characterized by dividing it into five major layers. The top layer served as a layer for lakes, rivers and landfill cap. The second layer represented the glacial outwash. Layer 3 was input to represent the landfill liner. A ten foot fractured bedrock layer, layer 4, was added below the outwash layer because the site of the landfill used to be a rock quarry. Layer 5 represents competent bedrock underlying the area. The hydraulic conductivities assigned to each layer are shown in Table 2.1.

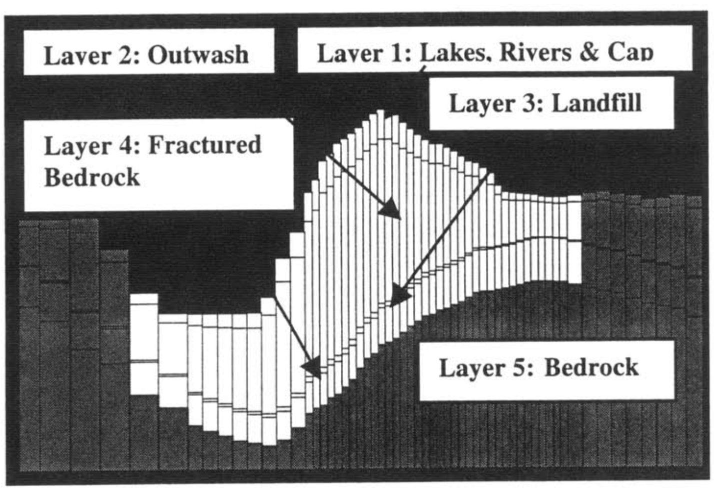

Figure 2.2: Model Layers

Table 2.1: Initial Hydraulic Parameters

Layer	$K_x = K_y$ (ft/d)	K_z (ft/d)
1	250	25
2	250	25
3	250	25
4	0.5	0.05
5	0	0

2.2.3 RIVERS AND LAKES

Lake Mirimichi, Turnpike Lake, Rabbit Hill Pond, Rabbit Hill Stream, the cranberry bogs, and Witch Pond as well as other tributaries were represented using the MODFLOW river package (Figure 2.3). River stage elevation was defined as the surface elevation. As required by the river package, conductances of the stream bed were assigned to individual cells using the following formula:

$C = KLW/M$

where C = conductance
K = conductivity of the river sediment (2 ft/d for rivers, 0.5 ft/d for lakes – Eckenfelder, 1998)
L = length of reach through cell
W = width of river in cell
M = thickness of river bed (1ft for rivers, 5ft for lakes – Freeze & Cherry, 1979)

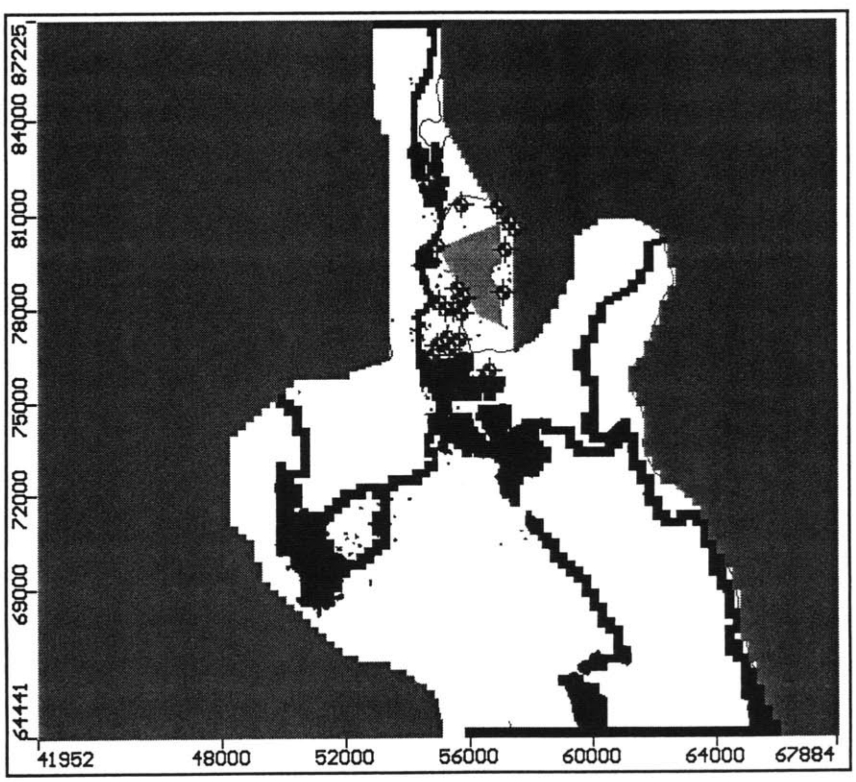

FIGURE 2.3: RIVER, LAKE, AND CONSTANT HEAD BOUNDARIES

2.3 MODEL CALIBRATION

After creating a running model, calibration is the next step done that is to ensure that the model is representative of the site. The heads predicted from the model should equal the heads from actual well data. Adjustments of the parameters are made until head level reproduction is acceptable. After adjustment of certain parameters, the final correlation is shown in Figure 2.4. The mean difference between calculated heads and observed heads was 1.44938; mean absolute error was 1.92465; RMS error was 2.04522. The end values for model parameters are in Table 2.2. K_X and K_Y represent horizontal hydraulic conductivities and K_Z is the vertical hydraulic conductivity.

TABLE 2.2: PARAMETERS FOR CALIBRATION

Layer	Kx = Ky (ft/d)	Kz (ft/d)
1	250	25
2	250	25
3	250	25
4	1	0.1
5	0	0
Recharge = 21"/yr		

Calibration was reached when the recharge rate over the landfill was set to one inches/yr and the hydraulic conductivities K_x and K_z for layers 1, 2, and 3 at the landfill were 25 ft/d and 2.5 ft/d, respectively. The groundwater flow output can be seen in Figure 2.4.

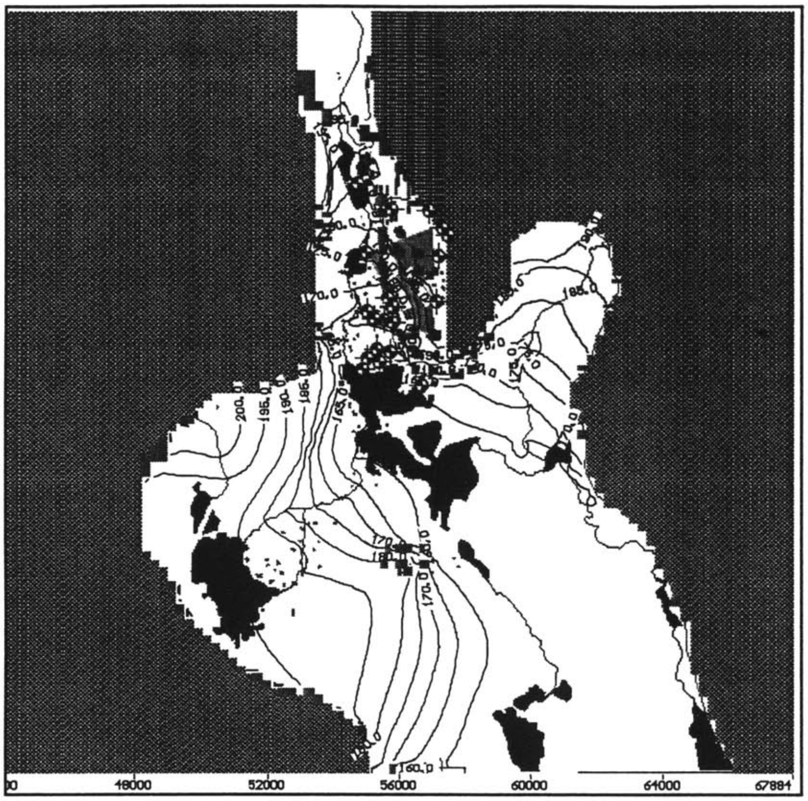

FIGURE 2.4: MODEL OUTPUT

2.4 LIMITATIONS

The following simplifications were made in the model:

1. Homogeneity of subsurface geology: The model simplifies the actual region and geologic parameters. Not only can the hydraulic conductivity vary within sediment type, but also it is not homogeneous throughout a particular layer. A few patches of till lenses have been detected in boreholes.

2. Steady-state simulation: The model is only calibrated for a steady state simulation; it does not take into consideration the seasonal effects of precipitation and groundwater recharge.

3. Fixed properties for lakes and rivers: All river cells were assigned the same conductivities for riverbed and same depth as were the lake cells.

4. Assumed till boundaries and fractured bedrock extent at landfill: Where the till ends around the landfill and how thick and the extent of the fractured bedrock layer was up to the discretion of the modeler. Historical knowledge and current plume situation were taken into account in developing this simple, yet representative model of the area.

3. PLUME MIGRATION MODEL

The groundwater contamination plume starts at the southwest corner of the landfill and extends downgradient, in a south-southwesterly direction, to Lake Mirimichi. The contamination from this plume has been detected in both the fractured bedrock and the overlying glacial outwash. The numerical groundwater flow model coupled with particle tracking was used for delineation of contributing areas for existing and proposed supply wells. MODPATH, a post processing package developed by USGS (Pollock, 1989) utilized the output from steady-state simulations with MODFLOW and computed the three dimensional pathline (particle tracking) of a water particle from the source to its fate. Particle tracking can help identify the aquifer source area from which a well is pumping water and thus aid in the analysis of pumping well impact on the contaminant plume.

3.1 PLUME COMPOSITION

Groundwater quality has been evaluated using data collected from ongoing groundwater monitoring and the Comprehensive Site Assessment (CSA). Originally, the water samples were tested for alkalinity, ammonia as nitrogen, chemical oxygen demand (COD), chloride, iron, lead, manganese, PH, nitrate and nitrite as nitrogen, specific conductance, sulfate, temperature, total dissolved solids (TSS), zinc, and kjeldahl nitrogen. In the early 1980's these tests were expanded to include testing the groundwater for volatile organic carbons (VOCs), arsenic, cadmium, chromium, mercury, dissolved oxygen, methane, and unknown organics. Since 1982, nine volatile organic compounds have been detected in the wells on a regular basis. These VOCs are 1-1 dichloroethane, 1-2 dichloroethane, 1-2 dichloropropane, 1-4 dichlorobenzene, benzene, chlorobenzene, chloroethane, and trans 1,2 dichloroethane. The concentrations of these VOCs ranged from 5-8 parts per billion and were found most often in wells located downgradient of the landfill. The most extensive sampling survey of the landfill was conducted in 1989 by GAI. This survey sampled all wells for conventional parameters and organics. The survey revealed that the wells located in the southwest corner showed anomalously high concentrations of several parameters. These parameters include alkalinity, ammonia, chloride ions, manganese, total dissolved solids, and organic compounds.

Although many contaminants have been detected in the groundwater plume throughout the years, only two consistently exceed the MMCL's of 2 ug/L and 5 ug/L respectively within the overburden and bedrock water bearing zones, vinyl chloride and 1,4-dichlorobenzene (Eckenfelder, 1998).

Vinyl Chloride (C_2H_3Cl) is a byproduct of the degradation of trichloroethylene. It is a manufactured substance used to make polyvinyl chloride (PVC). PVC is used to make a variety of products, including pipes, wire, cable coatings and furniture upholstery. Vinyl Chloride also results from the breakdown of other substances, such as trichloroethane, and tetrachloroethylene. Liquid Vinyl Chloride easily evaporates into the air as characterized by its low boiling point. It is not extremely soluble in water and is unlikely to build up in plants and animals. However, the vinyl chloride located in the contamination plume is dissolved. Its Octanol-Water partitioning coefficient suggests that it does not readily sorb onto soil. Vinyl Chloride is known to be a carcinogen as determined by the Department of Health and Human Services (DHHS). Exposure can result to liver cancer. Table 3.1 below is a summary of the chemical properties for vinyl chloride and 1,4 dichlorobenzene. These values have been extracted from the project report, where the plume composition is further described (Chen, Rahman & Woodworth, 1999).

TABLE 3.1: SUMMARY OF PROPERTIES

CHEMICAL PROPERTY	**Vinyl Chloride (C_2H_3Cl)**	**1,4 Dichlorobenzene ($C_6H_4Cl_2$)**
Molecular Weight (g/mol)	62.5	147
Melting Point (°C)	-153.8	53.1
Boiling Point (°C)	-13.4	174
Density (g/cm^3)	0.91	1.24
Solubility (mol/l)	0.04467	0.000776
Vapor Pressure (atm)	3.89	0.000912
Henry's Const. (L atm/mol)	22.38	2.24
Log K_{ow} (Octanol-Water Partitioning Coeff in mol/l of octanol per mol/l of water)	0.6	3.38

1,4 dichlorobenzene, also known as p-DCB or para-DCB is a chemical used to control moth, molds and mildew, and to deodorize restrooms and waste containers. When exposed to air, it slowly changes from solid to vapor where it breaks down to harmless products in about a month. It evaporates easily in to air from soil and water because of its low vapor pressure. It is not easily broken down by soil organisms and is not retained by plants or fish. Exposure to 1,4 dichlorobenzene can damage the lungs, liver, kidneys, and blood cells, causing anemia; it can also cause swelling of the eyes hand and feet. It can damage the nervous system, causing weakness, trembling, and numbness in the arms and legs. There is no direct evidence that 1,4 Dichlorobenzene can cause cancer in humans, however animals given very high amounts in water developed liver and kidney tumors. The DHHS has determined that 1,4 Dichlorobenzene 'may reasonably be anticipated to be a carcinogen'.

3.2 PARTICLE TRACKING (MODPATH)

The computer program MODPATH was developed by the USGS (Pollock, 1989) and is included with the Visual MODFLOW software for particle tracking. The MODFLOW manual describes it "as a tool used to calculate three dimensional particle tracking from steady state MODFLOW output". MODPATH carr compute three dimensional pathlines and positions of particles at a specified time. The program uses a semi-analytical tracking scheme based on the assumption that each directional velocity component varies linearly within a grid cell in the direction similar to the groundwater flow. For example if the initial position of a particle anywhere in a cell is given, the co-ordinates of any other point along its pathline within the cell, and the travel time between, them is computed. This is helpful in portraying a simple model of the contaminant plume, because groundwater and dissolved mass will move at the same rate (in the absence of other processes) and in the same direction (Domenico & Schwartz, 1998).

MODPATH only requires a reference starting time for both forward and backward particle-tracking simulation. It does not require specifying a discrete solution time step, thereby avoiding numerical errors associated with other algortihms (Barlow, 1994)

Particles can be placed around the perimeter of a circle or in a linear fashion for forward and backward advective pathline simulation. Forward tracking analyses pathlines for a particle from its starting point (the water table) to its fate (into a sink) following the numerical groundwater model output. This is advantageous for tracking the contaminant plume from the landfill to determine its fate upon reaching the lake. Backward tracking inc\volves pathline analysis against the groundwater flow. The particle's end-point is specified and MODPATH will determine its source. This is especially useful in determining the contributing area of a pumping well.

Although particle tracking is a useful tool in delineating the contributing areas of a well, the method requires a large amount of data (Barlow, 1994). There are certain limitations in using MODPATH. For example, particles must always start at the midpoint of cells. This can cause some problems for particles placed in the uppermost layer. If the water table is below the cell midpoint or if the cell is dry, the particles will not be transported. In areas where the local gradient is steep, or because of variable surface elevations, the particles may also stop prematurely (Pollock, 1989). MODPATH only simulates the advective component of particle transport and not the hydrodynamic dispersion and chemical reactions important to groundwater transport processes (Barlow, 1994).

3.3 Model Scenarios

In order to ascertain the extent of the plume and its future track, the numerical groundwater model was modified to mirror natural and seasonal variations. Plume migration can alter under varying field conditions and so it was necessary its pathway for the different seasons. To assimilate seasonal variations, certain model parameters such as, lake sediment conductivity, lake levels and recharge rates, were altered. There were basically two groups of scenarios, a pre-pumping group of models to reflect migration, if the proposed wells are never installed, and a post-pumping group to determine plume effects under the influence of pumping.

Following these changes, each model was allowed to run and achieve convergence. A numerical model is said to converge when the head difference between two cells is less than a value specified by the user. In this case the model was set to converge if the head difference between two adjacent cells were less than or equal to 0.1 feet.

The output from MODLFOW would then be used for particle tracking purposes. Two sets of particles were input into the model. The first set was positioned in a line at the southwest foot of the landfill to represent the contaminant plume. 20 particles were placed in the upper outwash layer (layer 2) and in the fractured bedrock layer (layer 4). These particles would be assessed under forward tracking. The second set of particles would be circumscribed around the Lake Mirimichi Wellfield and analyzed for backward tracking. This wellfield is not currently on-line, and so it was important to determine the change in plume path under pre-pumping and post-pumping conditions. These particles were also placed in the second and fourth layer, to determine the pumping well's zone of contribution. Changing model parameters could have an effect on the source of the wellfield and both layer two (the outwash layer) and layer four (the fractured bedrock layer) were potential sources.

As mentioned above there were two groups of scenarios: pre-pumping and post-pumping conditions. Pre-pumping conditions, where the pumps are off-line, simulated the present conditions. These scenarios were run and results were compared with the output from post-pumping conditions (pumps on-line) under the same parameters. The following list is a detailed description of how the parameters were modified. Each scenario implemented a combination of the following modifications.

1) Increased Sediment Conductivity – The initial sediment conductivity in Lake Mirimichi was set at 0.5 ft/day. The value was doubled to 1 ft/day to assess the infiltration capacity of the contaminant plume.

2) Decreased Lake Level – The base case model was calibrated under steady-state conditions, where Lake Mirimichi had an average head elevation of 160 ft NGVD. To simulate a dry season, the lake levels were lowered by 3 feet. The 3 feet adjustment was based on monitoring well data located around Lake Mirimichi. The wells were located around the circumference of the lake, as shown in Figure 3.1, and represent lake levels fairly accurately. The lowest head values observed was for September 1997 which are presented in Table 3.2. The average head drop was calcualted to be 3.3 feet that rounded to 3 feet.

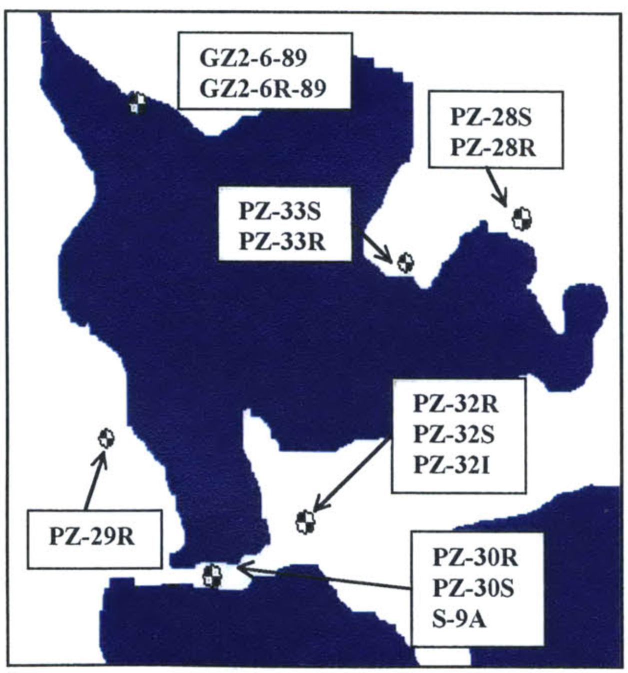

FIGURE 3.1: LOCATION OF MONITORING WELLS AROUND LAKE MIRIMICHI

Well No.	ELEVATION, NGVD
PZ-29R	157.17
PZ-30S	155.95
PZ-30R	156.18
PZ-32I	N/A
PZ-32R	N/A
PZ-32S	N/A
PZ-33S	156.36
PZ-33R	156.4
PZ-28R	156.59
PZ-28S	156.78
GZ2-6-89	157.83
GZ2-6R-89	157.79
S-9A	155.89

TABLE 3.2: DRY SEASON ELEVATIONS FOR SEPTEMBER 1997

3) Reduced Recharge Rates – A recharge rate of zero, the lowest recharge rate, was assigned to represent dry season or drought conditions
4) Reduced Sediment Conductivity – The sediment conductivity of Lake Mirimichi was lowered to a value of 0.01 ft/day to represent silty clay properties, which is typical of lake sediments (Freeze & Cherry, 1979). This may force the plume to bypass the lake and migrate underneath it.
5) Increased Lake Levels – The surface elevations at Lake Mirimichi was increased by a foot to simulate wet season conditions. This was to reduce the plume infiltration rate into the lake by increasing its heads and assess the plume pathway as a result.

4. Supply Well Characteristics

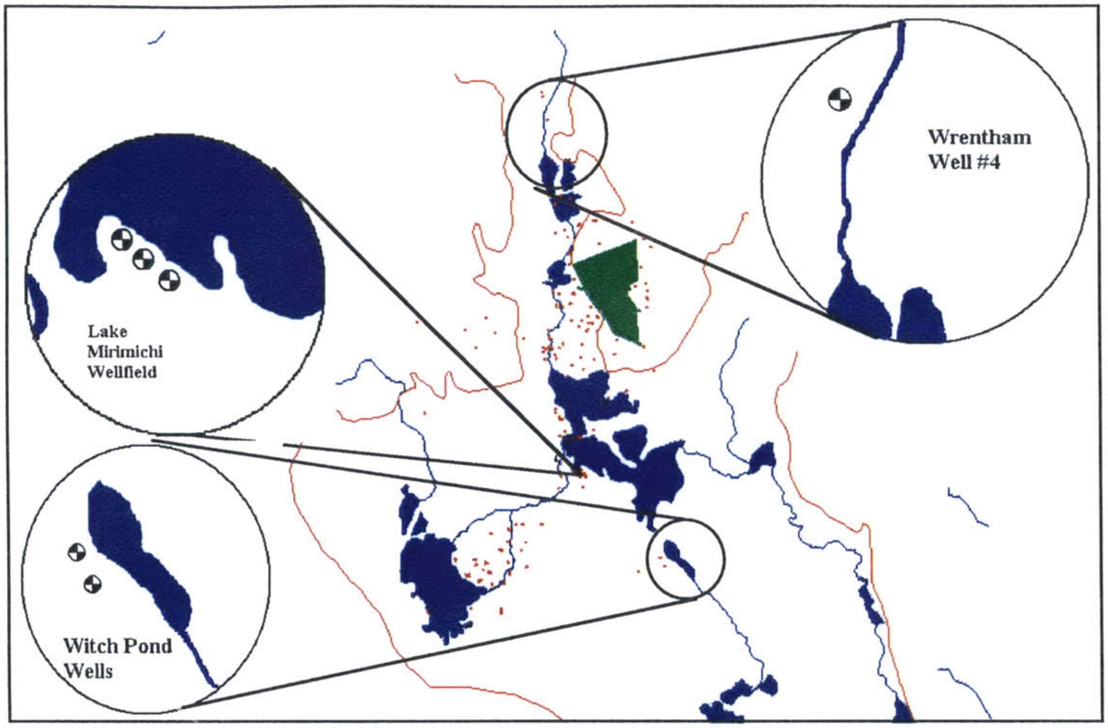

FIGURE 4.1: LOCATION OF PUMPING WELLS

4.1 Well Location

As shown in Figure 4.1, there are three sets of wells in the vicinity of the landfill. Each well is described separately in the following sections

4.1.1 Wrentham Well No. 4

The town of Wrentham currently operates the Wrentham Well No. 4. It is located north of the landfill by Rabbit Hill Stream. This pump is currently on-line and has an approved pumping rate of 600 gallons per minute. Numerous studies were undertaken to investigate the possibilities of plume migration towards the well resulting in contamination

4.1.2 Lake Mirimichi Wellfield

The proposed Lake Mirimichi wellfield is a series of three production wells positioned in a northeast to southwest direction in the southwest corner of Lake Mirimichi. The wellfield is under Plainville jurisdiction. The landfill is 4000 feet directly upgradient of the wells. The aquifer underneath was relatively shallow and drawdown as a result of pumping had to be kept at a minimum. Distributing the pumping rate among three wells instead of one was the solution to pumping reasonable rates, but at the same time inducing minimum drawdown. The three wells have DEP approval to pump 300 gallons per minute in total. The wells penetrated to a depth of 30 feet from the surface, of which the whole extent was screened for pumping purposes. The Dufresne & Henry Inc. report performed pumping tests and a Zone II analysis for these wells, which is described in Section 4.2.1.

4.1.3 Witch pond Wells

The town of Foxborough has plans to install two wells near Witch Pond, a surface water body south of Lake Mirimichi. These wells were planned to extend 100 feet from the surface of which the last 10 feet were screened for pumping purposes. These were scheduled to pump 500 gallons per minute total. Whitman & Howard prepared a Zone II delineation for these wells which is described in Section 4.2.2. Table 4.1 below summarizes the pumping rates of the wells mentioned above.

TABLE 4.1 PUMPING RATES OF PUBLIC SUPPLY WELLS AROUND PLAINVILLE

Pump Name	Pumping Rate
Lake Mirimichi Wellfield	300 gpm
Witch Pond Wells	500 gpm
Wrentham Well No. 4	600 gpm

4.2 PREVIOUS STUDIES ON PROPOSED WELLS

Various consulting firms have performed Zone II studies on the Lake Mirimichi wellfield and the Witch Pond wells. Zone II is necessary to determine the largest area of the aquifer contributing to a water supply well under the severest pumping conditions and no recharge. Their conclusions pertinent to this study are summarized below.

4.2.1 DUFRESNE & HENRY STUDY

Dufresene & Henry Inc (Nov, 1997) performed a pumping test study focusing their model on the aquifer around Lake Mirimichi and a Zone II analysis, which is the determination of the largest area of an aquifer that contributes to a well under the severest pumping conditions and no recharge rates. They inferred that the Zone II delineation of the wellfield does not extend as far as the landfill. Twenty four hour pump tests at the approved pumping rates only caused depression as far as the northern shore of the lake. By particle tracking most water was bound to originate from the till hill south of Lake Mirimichi. Water balance indicated 74% of the water withdrawn after the 180-day simulation originated from Lake Mirmichi. Dufresne & Henry used a seventy five percent (75%) safety factor for the total safe yield calculation and recommended 300 gallons per minute. They based their findings on Nields et. al. (1999) study who implied groundwater underflow could only occur if the aquifer were thicker, the vertical hydraulic conductivity were lower or the hydraulic conductivity of the lake sediments were lower. These aspects will be investigated in this study.

4.2.2 Whitman & Howard Groundwater Model

Whitman & Howard, Inc. (Feb 1996) performed an analysis of the possible groundwater flow beneath Lake Mirimichi from the Plainville landfill to the Witch Pond wells. They concluded stated that there was no significant groundwater flow from the northern end of the lake to the southern end. This was because Lake Mirimichi is a large body of water with relatively constant head and a direct connection to the groundwater beneath it. The northern end of the lake is a large discharge area, which funnels the majority of the groundwater upward into the pond. The southern end of the lake is a strong recharge area because the head of the lake is higher than the aquifer to the south. Whitman & Howard also concluded that groundwater flow is mainly upward into the lake from the groundwater beneath it, inspite of the 70 feet outwash thickness. Therefore horizontal flow appeared to be overwhelmed by the vertical flow.

5. Pre-Pumping Results

The first set of model runs was conducted under non-pumping conditions. This was to represent current groundwater flow conditions. As mentioned in Chapter 4, most of the wells are currently under construction and will go on-line in the near future.

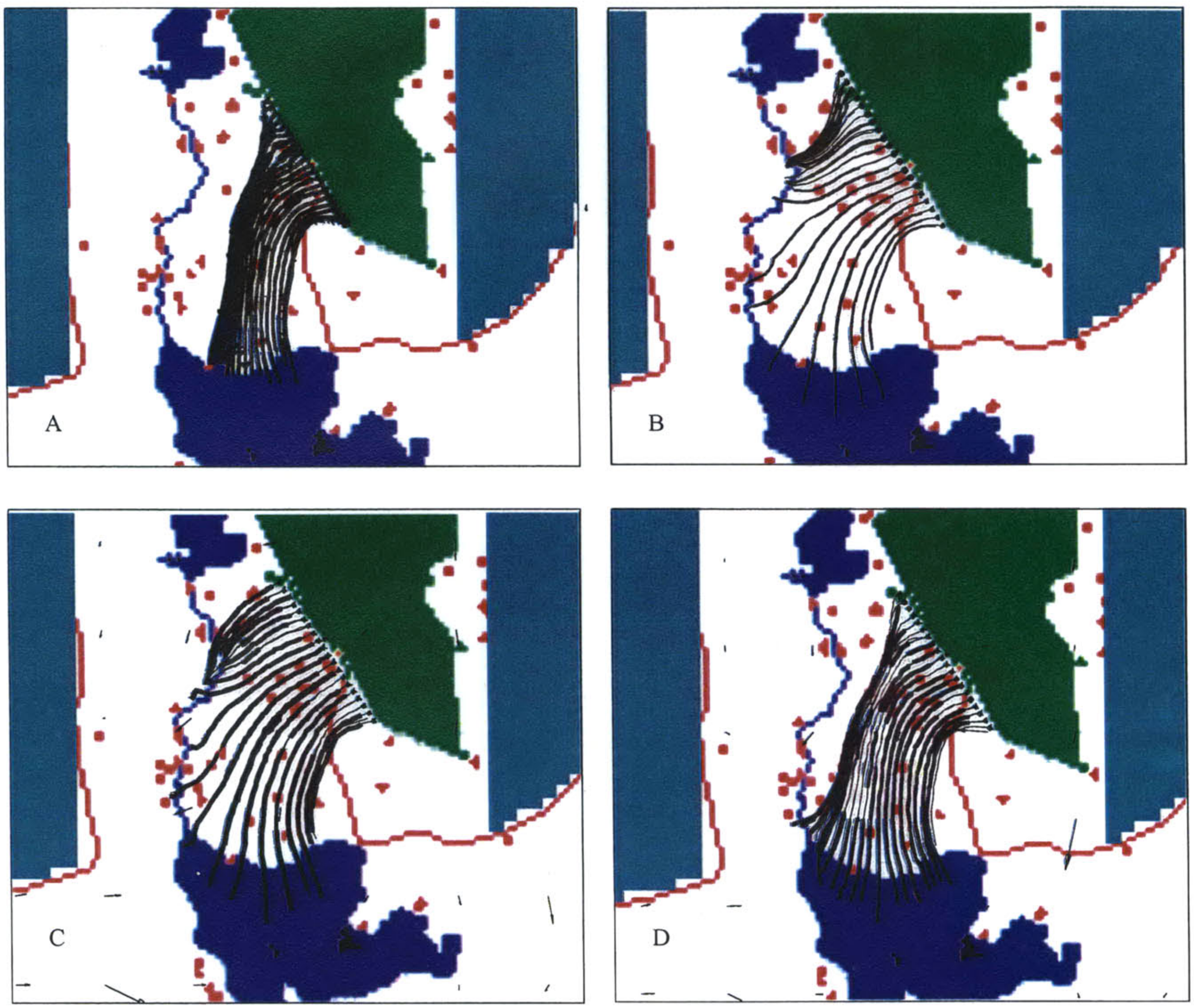

Figure 5.1: Pre-pumping conditions A) Base Case; B) High lake sediment conductivity; C) Low lake levels and high sediment conductivity; D) Low recharge high sediment conductivity and low lake levels.

TABLE 5.1 PRE-PUMPING FLOW CALIBRATION RESULTS

Non-Pumping Scenario	Mean Error	Mean Absolute Error	RMS Error	Head Difference (ft)
Base Case	1.44938	1.92465	2.04522	0
High Sediment K	3.06083	3.48634	3.84745	+1.61
Low Lake	3.18319	4.18127	5.68917	+1.73
Low Recharge	0.868167	2.1558	2.8653	-0.58

Figure 5.1 compares the particle tracking results between the base case condition and three scenarios. Table 5.1 presents the mean error and head difference, after flow calibration, between the base and three scenarios. Fig 5.1(a) represents the base case model. This output was achieved after performing calibration and sensitivity analyses. The hydraulic heads approximate those recorded in the field. Particle tracking revealed the plume pathway of all twenty particles from both layers. The particles generally traversed towards the lake. This steady-state output also indicated that the plume was currently infiltrating from the groundwater into the lake through the sediments. The abrupt discontinuation of the particle pathlines suggested that the contaminants disappeared into the lake. This was because the lake acted as a sink. Results were representative of current field conditions, because groundwater quality tests (Environmental Monitoring Plan, 1994) implied that the plume was presently penetrating into the lake.

Fig 5.1(b) was an output as a result of increasing sediment conductivity in Lake Mirimichi from 0.5 ft/day to 1 ft/day. Flow calibration results indicated water elevation increased by 1.6 feet. In this case almost 50% of the particles were diverting towards nearby streams and other water bodies relatively downgradient of the particle starting point. A higher conductivity allowed accelerated flow as per Darcy's Law (Freeze &

Cherry, 1979) and so the particles seeped into sinks and constant heads faster than before. This resulted in a 1.6 feet increase in the water table elevations.

The next simulation was run under high lake sediment conductivity and lake levels three feet lower than normal. The particles followed the same path as in the second simulation, but the extent of infiltration into the lake was slightly increased as shown in Figure 5.1(c). This simulation also resulted in a water table 1.73 feet higher than normal. Lower lake levels created a larger head difference, causing increased flow into the lake. This scenario caused the contaminants to migrate further into the lake.

The last figure, Figure 5.1(d) was simulated under zero recharge rates, low lake levels and high sediment conductivity. The flow calibrations resulted in a decline of about 0.58 feet in the water table. In this case, the plume infiltration rate was slightly inhibited. Lower recharge produced a lower water table and diminished flow rates. The particle tracking results due to zero recharge were almost similar to the base case except that there was increased infiltration.

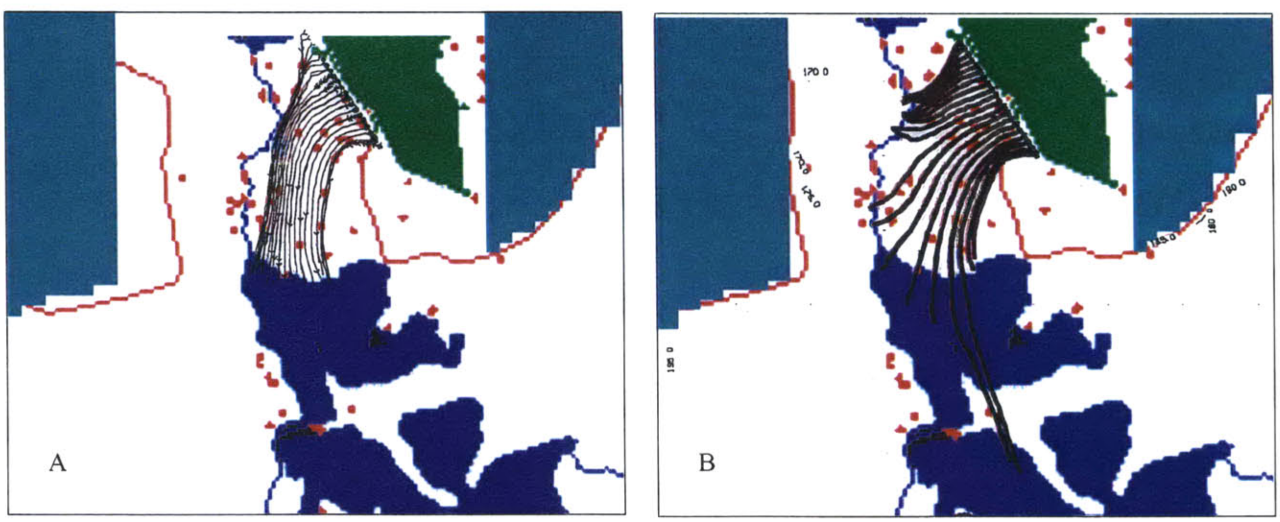

FIGURE 5.2: PRE-PUMPING COMPARISONS; A) BASE CASE; B) HIGH LAKE LEVELS, LOW SEDIMENT CONDUCTIVITY AND NO RECHARGE.

Figure 5.2 illustrates a comparison between the base case, and a scenario where the sediment conductivities were decreased from 0.5 ft/day to 0.01 ft/day, the surface water table was increased by one foot, and recharge was set from 21 inches/yr to zero inches/yr. The water table elevated by 2.8 feet. It was noted that two of the twenty particles seeped under the lake and almost reached the vicinity of the proposed Lake Mirimichi wellfield, in the southern leg of the lake. Simulation results under pumping conditions could show whether the particles originating from the landfill were able to reach the pumping wells.

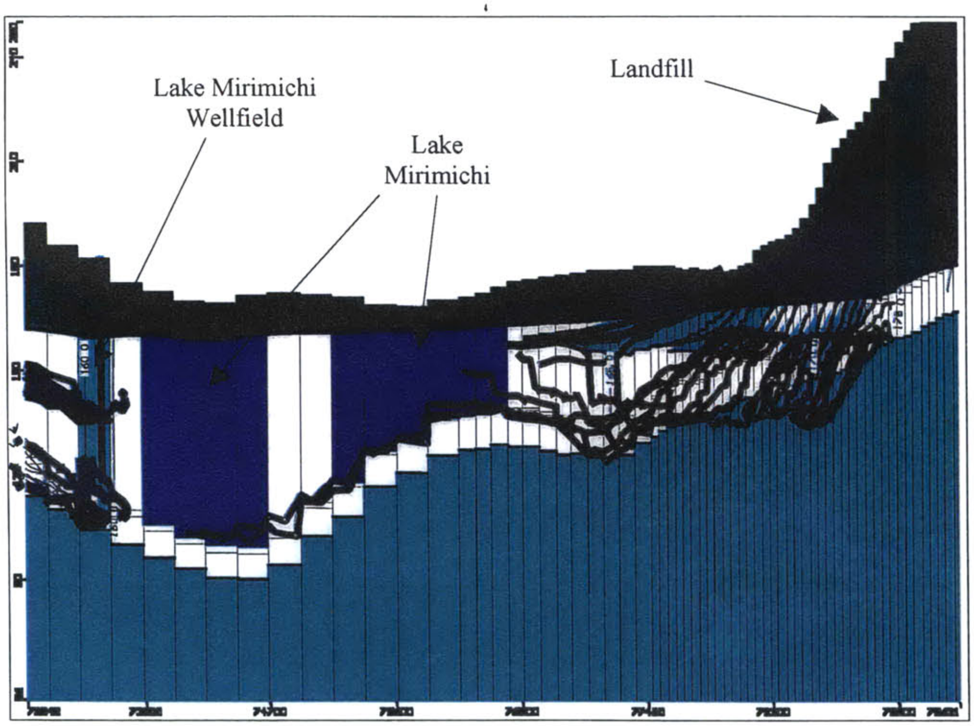

FIGURE 5.3: A NORTH SOUTH CROSS SECTION OF PARTICLE TRACKING RESULTS FOR HIGH LAKE LEVELS, LOW SEDIMENT CONDUCTIVITY AND ZERO RECHARGE

Figure 5.3 is a cross section illustrating the pathlines traversed under the last scenario. This indicated that particles could travel through the fourth layer, the fractured bedrock layer, if field conditions were similar to the parameters used in this scenario.

6. Post-Pumping results

The scenarios described in Chapter 5 were re-simulated under pumping from the Lake Mirimichi Wellfield, the Witch Pond wells and the Wrentham Well no. 4 simultaneously. The numerical groundwater models were then used in forward particle tracking to represent plume migration and backward particle tracking to determine the pumping well's zone of contribution. The results are presented in separate sections below.

6.1 Forward Tracking Results

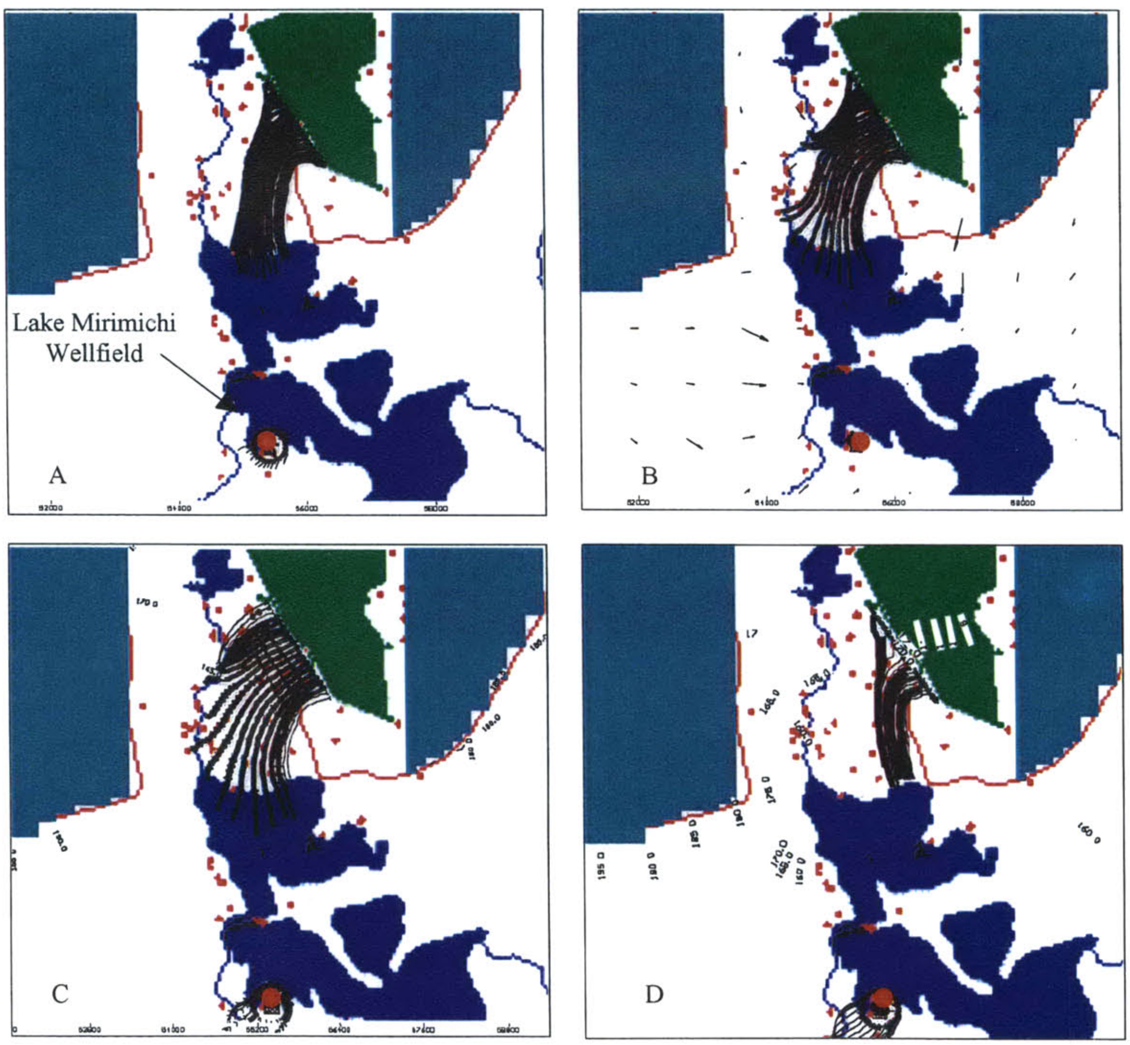

Figure 6.1: Post-Pumping Particle Tracking Results; a) Base case; b) High lake sediment conductivity; c) Low lake levels and high sediment conductivity; d) Zero recharge, low lake and high sediment conductivity.

These particle-tracking results were the outcome of performing a forward tracking simulation for twenty particles, being released from the southwestern foot of the landfill, but arranged in a line. The particles followed groundwater flow under steady-state simulations. Their end-points represented the ultimate position of a particle when the groundwater flow model reached steady state conditions. The flow calibration results are presented in Table 6.1 below.

TABLE 6.1: POST-PUMPING FLOW CALIBRATION RESULTS

Pumping Scenario	Mean Error	Mean Absolute Error	RMS Error	Head Difference (ft)
Base Case	1.42817	1.91798	2.03736	0
High Sediment K	2.18924	2.61436	2.82367	+0.76
Low Lake	3.18305	4.18141	5.6893	+1.75
Low Recharge	-0.406706	1.46095	1.99218	-1.83

Figure 6.1(a) is the base case scenario under pumping conditions. The particle pathline was very similar to its non-pumping counterpart from the previous section except that the pathway extended further into the lake. This effect may be due to minimal pumping being done at the Lake Mirimichi wellfield. The presence of a three-well configuration reduced the drawdown effect, but should have increased the contributing area. There was no apparent change in the forward tracking simulation between systems that were pumped and non-pumped.

Figure 6.1(b) was the result of pumping under high lake sediment conductivity. The flow model behaved similarly to that under non-pumping conditions. Table 6.1 indicated a slight head elevation increase of 0.76 feet in the observation wells. Almost 50% of the particles permeated towards the nearest water body. An increase in sediment conductivity from 0.5 ft/day to 1 ft/day allowed particles to flow faster into the water body, which acted as sinks. This could mean that a contaminant particle disappeared rapidly in to the sink.

Leaving the lake sediment conductivities at 1 ft per day and only declining lake levels by three feet resulted in the groundwater model output as shown in Figure 6.1(c). The pumping scenario had no effect on the infiltration rate of particles into the lake. Lower lake levels caused more particles to be drawn into the lake to compensate for the drop in flow and head. A 1.75 feet increase in water table at the observation wells could be the reason for such a slow infiltration rate.

Figure 6.1(d) results were slightly different from the rest. This scenario composed of zero recharge rates (as opposed to 21 inches/yr. in the base case), low lake and river system and high sediment conductivity. This scenario was the equivalent of a drought period experienced by the region. Particle tracking implied all of the particles trying to reach the lake by selecting the shortest path possible. The particles followed a direct southward flow and reached the lake, an active sink, at the closest shore, the northern part. This path was distinctly different from that under a pre-pumping scenario. The plume did not curve gently towards the west, as in a pre-pumping case, but curved sharply southward. The plume was more focused and not dispersed as in the other results. This non-dispersive behavior could be supported by the fact that the water table dropped 1.83 feet as recorded by flow calibration results. Pumping, however, exhibited no effects on the plume traveling directly into the supply wells.

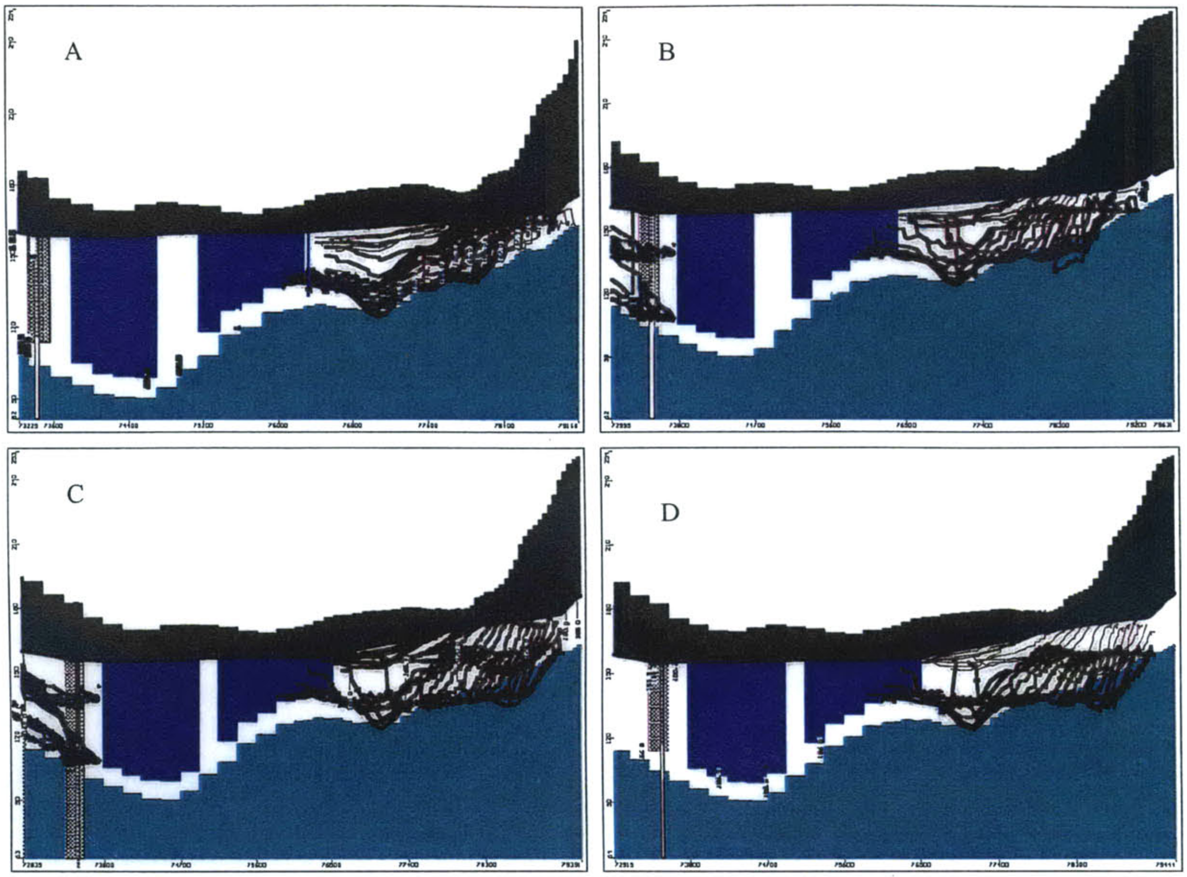

FIGURE 6.2: POST-PUMPING PARTICLE TRACKING RESULTS, NORTH-SOUTH CROSS-SECTIONAL VIEW ACROSS THE LANDFILL, LAKE MIRIMICHI AND THE LAKE MIRIMICHI WELLFIELD; A) BASE CASE; B) HIGH LAKE SEDIMENT CONDUCTIVITY; C) LOW LAKE LEVELS AND HIGH SEDIMENT CONDUCTIVITY; D) ZERO RECHARGE, LOW LAKES AND HIGH SEDIMENT CONDUCTIVITY

Figure 6.2 are the same particle results as before but viewed north south cross-sectional view of the system. The figures show the Plainville landfill to the right, the lake in the middle colored dark blue and the Lake Mirimichi supply wells at the left with their depths and screening intervals. Particle tracking results indicated most of the travel was in layer four, the fractured bedrock layer. Some of the particles traveled through the no-flow zone, denoted by the light blue colored region in the bottom. This was due to the cross-section taken from a point where the no-flow boundary was at higher elevation. The particles traversing a no-flow zone were actually travelling through the fractured bedrock in the cross section behind it. MODFLOW pictured the pathlines for the whole model in one cross-section irrespective of which cross-section was viewed. As shown in Figure 6.3, particle pathlines appeared similar in all cases. This meant that altering the sediment conductivity, the lake levels and the recharge rates did not cause the contaminant to bypass under the lake, but rather accelerated the infiltration rate into the lake.

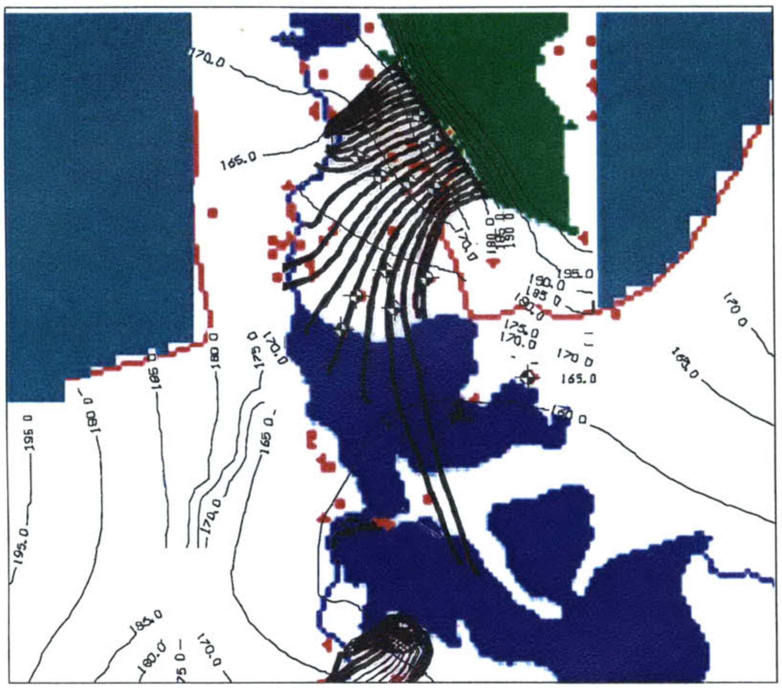

FIGURE 6.3: PUMPING SCENARIO UNDER HIGH LAKE LEVELS AND LOW SEDIMENT CONDUCTIVITY

An interesting result was obtained when particle tracking was performed under increased lake levels and low sediment conductivity. The results are shown in Figure 6.3. In this scenario, the lake sediment conductivity was reduced from 0.5 ft/day to 0.01 ft/day. The lake levels were also increased by a foot. This caused fewer particles to infiltrate into the lake and bypass under it to the southern part of the lake. This was a potential for contaminant pathway as was suspected in the hypothesis. The water table also increased by 2.5 feet.

6.2 BACKTRACKING RESULTS

Backtracking was performed around the Lake Mirimichi wellfield under pumping conditions to determine its source of the water under these parameter changes. The results are shown in Figure 6.4 below.

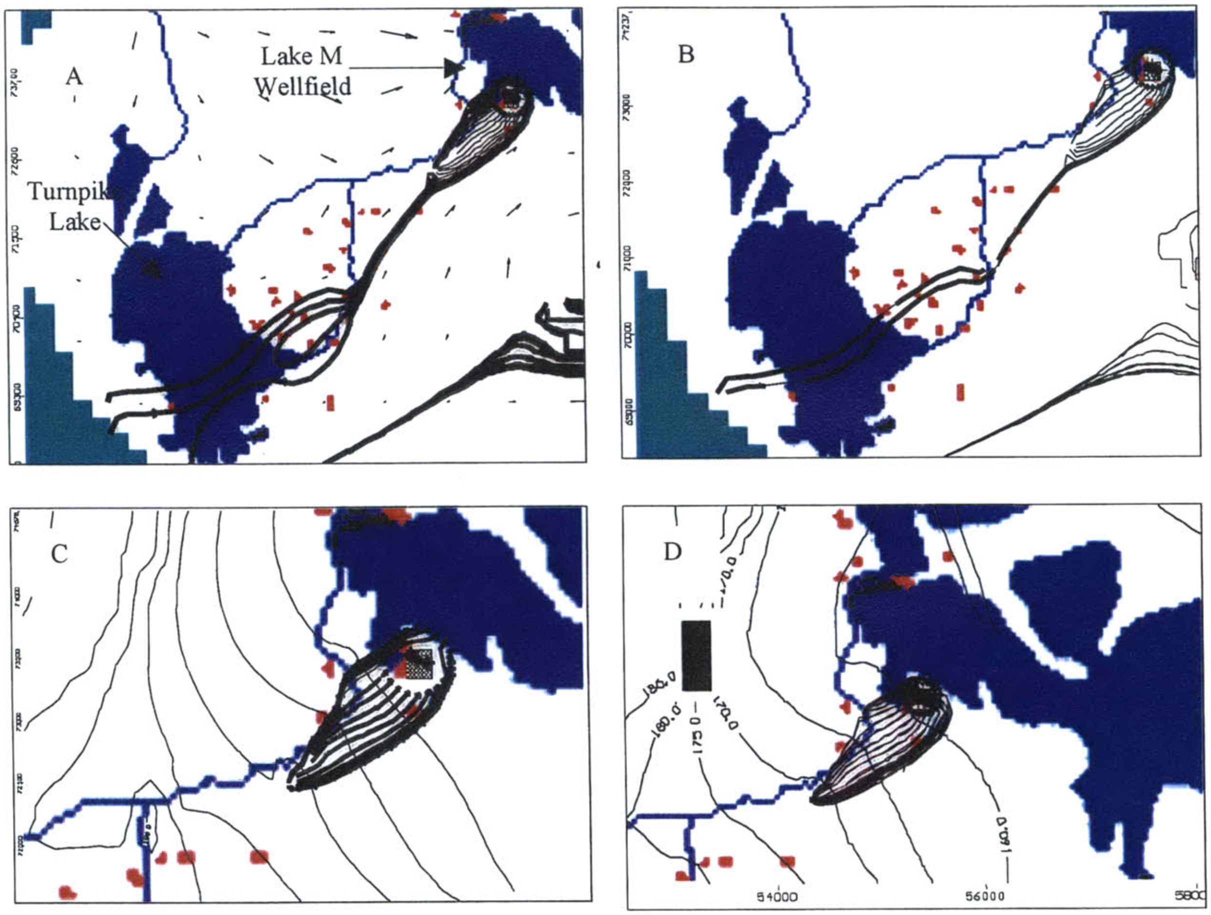

FIGURE 6.4: BACKWARD PARTICLE TRACKING RESULTS AROUND LAKE MIRIMICHI WELLFIELD; A) BASE CASE; B) HIGH SEDIMENT CONDUCTIVITY; C) LOW LAKE LEVELS AND HIGH SED K; D) ZERO RECHARGE, LOW LAKE AND HIGH SED K.

The base case scenario and the increased sediment conductivity behaved similarly, indicating that sediment conductivity had minimal impact on the source of the supply wells. The steady state conditions implied that the source was from Turnpike lake, however minimum knowledge of aquifer data in this area could have resulted in a different outcome. The model did not represent this area of the aquifer as accurately as possible, because the outwash layer in this region was depicted to be deeper than recorded from field data. This may have distinct difference in the source of the well, so accurate predictions could not be made through back tracking. Figure 6.5 illustrates another backward particle tracking result under the final scenario where the lake levels were increased by a foot and lake sediment conductivities were dropped from 0.5 ft/day to 0.01 ft/day with zero recharge rate.

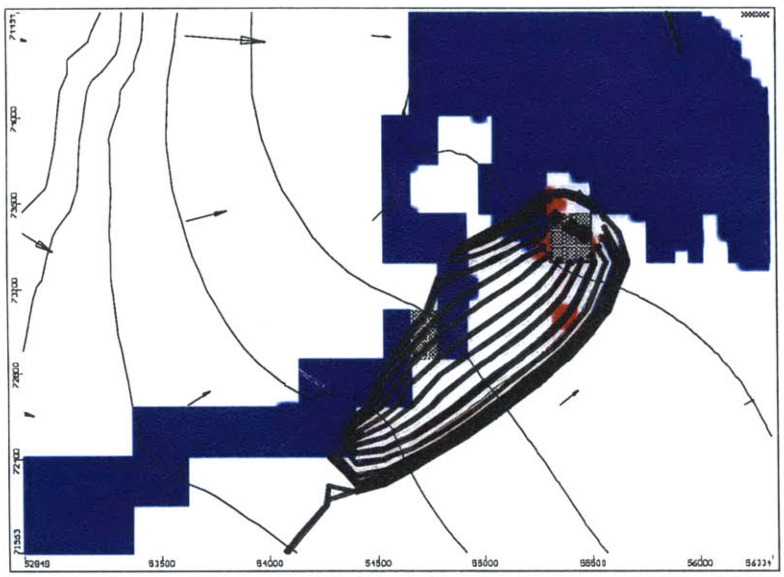

FIGURE 6.5: BACKWARD PARTICLE TRACKING RESULTS AROUND LAKE MIRIMICHI WELLFIELD WITH ZERO RECHARGE, HIGH LAKE LEVELS AND LOW SEDIMENT CONDUCTIVITY.

The particle tracking results indicated some particles were drawn from Lake Mirimichi, but the majority of particles originated from the Turnpike lake and Turnpike stream.

7. Conclusions

From extensive particle tracking results, the model indicated that the supply wells in Lake Mirimichi did not draw solely from the lake but had other surface water sources like Turnpike Lake and its streams. Increased sediment conductivity caused the plume to infiltrate more rapidly into the lake. Reduced recharge had the same effect. Increased lake levels and lower sediment conductivity cause a portion of the plume to bypass the lake and remain in the groundwater.

Both forward and backward particle tracking were sensitive to model parameters. The model was in many ways a rough approximate of reality and particle-tracking results were only as reliable as these models. Forward particle tracking results suggested that there was a potential for about 10 % of contaminants to bypass under the lake and reach the southern part of the lake, but not necessarily reach as far as the supply wells. The low boiling point of vinyl chloride, one of the main constituents of the plume, caused it to volatilize upon infiltration into the lake from groundwater (Eckenfelder, 1998), and so there was a slim chance for well contamination. But more data and continued monitoring results could ascertain the results of this model.

There were certain limitations to this model; for example, the simulations were performed under steady-state conditions. A transient model would have accurately represented lake level fluctuations with seasonal variation and be more representative of the site. But the availability of data for inputs and calibration was limited and may have been possible after more data collection.

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